Maximizing The Efficiency Of A 4-cell FK Module

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Abstract. The outdoor measurements of both a single-cell and a 4-cell CPV modules reaching, respectively, maximum peak efficiencies of 36.0% and 34.8% (both corrected @T_{cell}=25ºC) are presented. This is the result of the joint effort by LPI and Solar Junction to demonstrate the potential of combining their respective state-of-the-art concentrator optics and solar cells. The LPI concentrator used is a Fresnel Köhler(*FK*), which is an advanced nonimaging concentrator using 4-channel Köhler homogenization, based on a primary Fresnel lens and a free-form secondary glass lens. Solar Junction's cell is a triple-junction solar cell with the A-SLAM^{TM} architecture using dilute-nitrides.

INTRODUCTION

The one fact that draws more attraction to High concentration photovoltaics (*HCPV*) as a real alternative for electricity generation is the high efficiency of the concentrators solar cells. A group of companies and institutions including *Soitec* and *Fraunhofer ISE* holds the current world record efficiency, with a four-junctions (*4J*) prototype cell attaining 44.7% conversion efficiency, at a concentration of 297× [1].*Solar Junction* manufactures a commercial cell with its *A-SLAM*^{TM} lattice matched architecture reaching efficiencies beyond 44% at a much higher concentration (947×) [2]. This efficiency nearly doubles that of the best commercial 1-sun silicon solar cells, and there is a clear path for further efficiency improvements by increasing the number of junctions. However, to take full advantage of this high efficiency, these cells must be combined with concentrator optics that provide the required high concentration with a high optical efficiency and sufficient tolerances (reflected in the concentrator acceptance angle) to keep the cost low and the efficiency high at the real world array level. Additionally, the concentrator must also provide good spatial and spectral homogeneity of the cell illumination for the three junctions, which is an aspect that has been probably underestimated so far [3].

The *FK* concentrator [4] enables all these performance features without giving up simplicity: it is still a system based on easy-to-manufacture Fresnel lens primary optic and a lens-type secondary optic, both compatible with mass production. The outstanding performance of the *FK* has been demonstrated by means of several tests [5] and the technology is commercially available since 2012.

During the past few months, *LPI* and *Solar Junction* have been collaborating to design and manufacture a proof-of-concept prototype to demonstrate that very high module efficiencies can be obtained by combining their optics and cells technologies, and that this can be achieved with both very high concentration and high acceptance angle. The work and tests results gathered along one year with two different prototypes (a monomodule, comprising one single cell, and a module, comprising four cells) will be detailed along the text.

CONCENTRATOR MODULE DESIGN

There are two main components in a *CPV* module: the solar cell and the optical train. In order to tackle an upper bound performance, the optical design needs to consider all spectral features of both the sunlight and the solar cell response, junction by junction.

The goal is on the one hand to collect a short circuit photocurrent I_{sc} out of the concentration as high as possible and on the other to assure the *IV* curve of the power delivered has a high *Fill Factor FF*. The first goal can be achieved by designing the optical surfaces and selecting the type of materials such that the optical losses (mostly Fresnel reflections and absorption in a system like the *FK*) are reduced to a minimum in the entire range of wavelengths linked to all the three junctions, or at least in the spectral range of junctions that tend to limit the output (Top and Middle junctions in most *3J* solar cells).

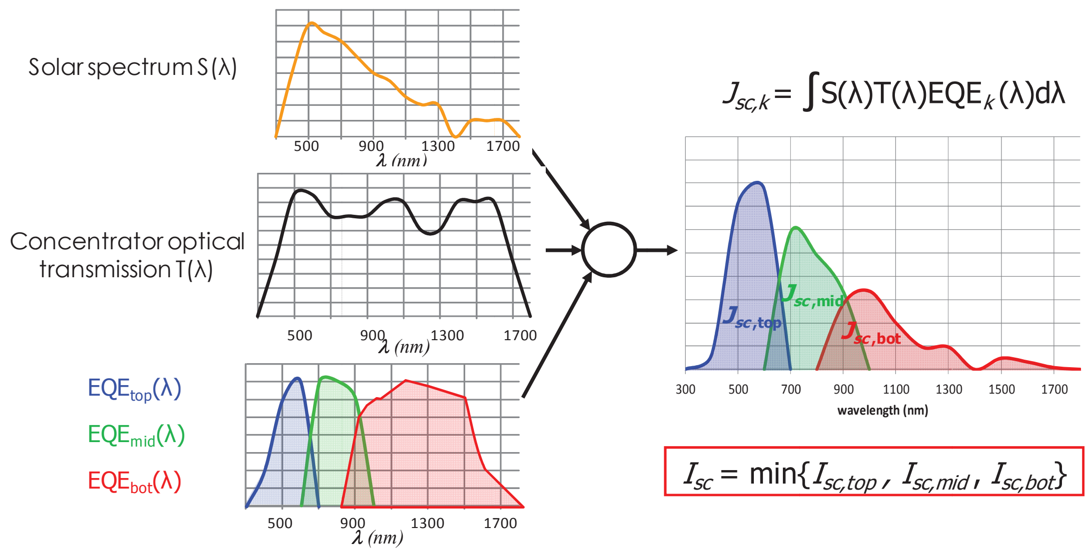

FIGURE 1 The optical design should take into account the spectral content of the sun and the spectral response of the solar cell, so the appropriate materials and optics architecture can convey as much power as possible to the cell, that in turns delivers the maximum photocurrent possible (which is the minimum among the three junctions I_{sc})

The second goal needs a uniform irradiance onto the solar cell, without significant variations for different spectral regions. The effect of having light spots whose shape varies for different wavelengths, cell positions or incidence angles have been described before in [3]. In that work, unlike other Fresnel-based systems, the *FK* demonstrated its immunity to this problem thanks to an almost perfect uniform irradiance throughout the entire sun spectrum and for all incident angles within its acceptance angle.

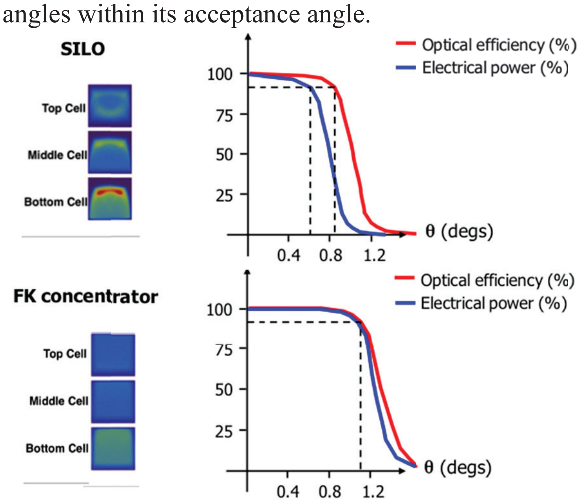

FIGURE 2. Negative effects on a CPV module performance due to irradiance and chromatic dispersion. Left plots show the irradiance profiles for the three sub-cells (top, middle, bottom) when the module is misaligned 0.6°, for a Fresnel-based concentrator as the SILO (top) and for the FK concentrator (bottom). Right curves show the optical efficiency (in red) and electrical power (in blue) curves and their evolution with the module misalignment.

This last issue can be graphically explained through FIGURE 2, which shows simulated irradiance profiles for two different optical concentrators performing at 0.6° off-axis position. The irradiance profiles of the different sub-cells (top, middle and bottom) are shown for a SILO [6] and for an FK concentrator, both of them presenting identical optical parameters (C_g, *f*-number, materials). The curves show that, while the SILO is delivering around 90% of the nominal electrical power at a 0.6° off-axis situation, the FK concentrator is well above a 99% value.

A careful selection of the design parameters is needed to attain the best-possible *FK* concentrator. Among them, the most challenging ones are the geometrical concentration (C_g), the compactness (defined by the *f*-number) and the optical materials. An exhaustive analysis of the cell performance under the illumination produced by the *LPI* concentrator has been carried out on the different alternatives initially proposed. This analysis has included detailed ray tracing simulations of the concentrator carried out by *LPI* to obtain the transmission function $T(x,y,\lambda)$, where λ is the wavelength of the light (for values within the *SJ* solar cell spectral range of interest) and x-y are the coordinates that define the position on the solar cell surface. This information has served as the input for SJ to model the cell under an arbitrary sun spectrum (but with special interest in the AM1.5d), using a discretized circuit model with lumped components which can be analyzed with a standard circuit analysis software for non-linear electric circuits (such as PSPICE). Modeled efficiencies surpassing 36% for the module were predicted, which encouraged the team to prove it out in real prototypes. The final design has

C_g=1024× (defined over illuminated area) and equivalent *f-number*=1, with an acceptance angle of α=±1º.The design has been optimized to provide maximum irradiance uniformity. The *POE* is manufactured using Silicone on glass (*SOG*) while the *SOE* is a silica glass molded part.

MONOMODULE MEASUREMENTS

The experimental results shown in this section correspond to outdoor measurements carried out on the first complete single-cell module, which was assembled by *LPI* with a custom concentrator rig.

FIGURE3 Monomodule installed at the UPM-CeDint roof tracker. The optically active entry area has been masked for a fair calculation of power available at the entry aperture.

The tests were run with an *I-V* curve tracer variable load at the CeDint facilities of the Technical University of Madrid (located in the west Madrid area, at latitude: 40,4045, longitude: -3,835, see FIGURE 3) There are two different sets of measurements collected with this prototype: the first of them lasted 1.5 hours on April 18th 2013, while the second was carried out on August 20th 2013 during 2 hours.

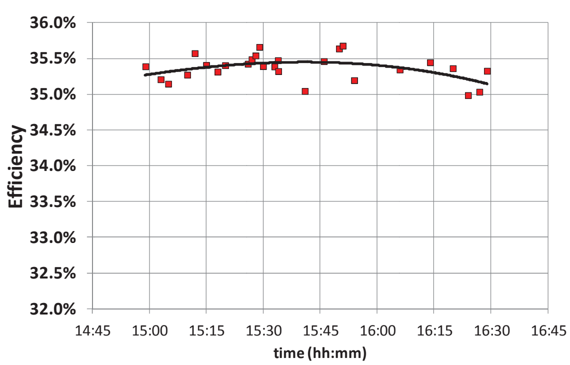

FIGURE 4 Set of April 2013 measurements, corrected at 25°C.The maximum efficiency achieved was 35.7%.

FIGURE 4 shows the measured efficiencies for the first set of measurements (April), ranging between 35-35.7% (@25ºC). The open circuit voltage values (V_{oc}) were very stable (3.32 V) during these measurements. The tests were repeated in August, obtaining in this case a higher peak-efficiency (36%, temperature corrected), as FIGURE 5 shows.

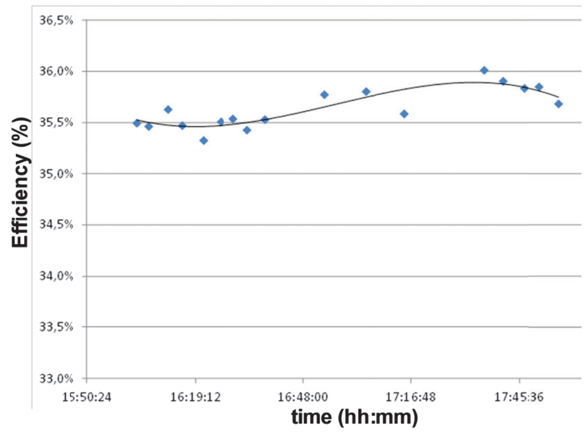

FIGURE 5 August 2013 measurements, corrected at 25°C.

Notice the efficiency values are in the 35.4-35.9% range with instantaneous efficiencies up to 36.0%. FIGURE 6 shows the I-V curve of the highest instantaneous efficiency measured.

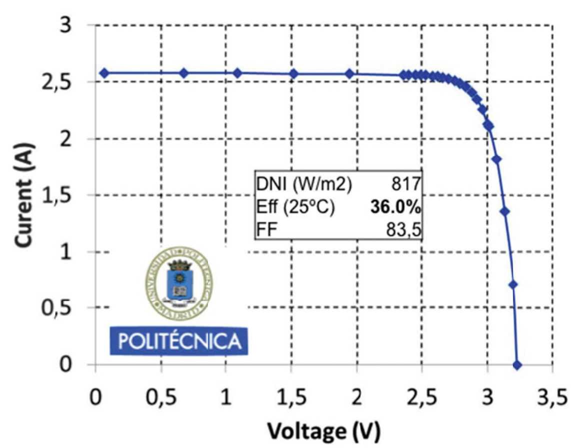

FIGURE 6 The *IV* curve of the maximum efficiency attained in August has a *FF* of 83.5%, and was measured with an irradiance of 817W/m^2

MODULE MEASUREMENTS

The monomodule concentrator rig is also compatible with the 4-units module. In this case, the single lens POE panel is replaced by a set of four replicas of this 0.16×0.16m^{2}lens and the back plate comprising one single receiver (*SOE* + *CCA*) by another one gathering four, as FIGURE 7 shows.

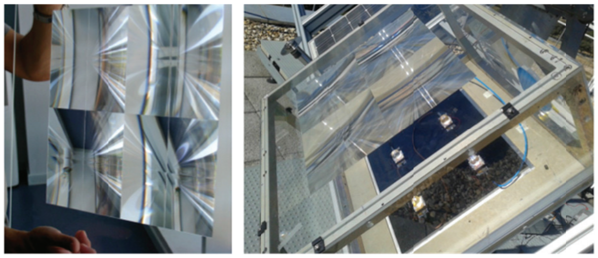

FIGURE 7 The picture on the left shows the 4-units POE panel and the right one shows the full module (including POE, holding rig, back plate and receivers) assembled and mounted on the tracker

The module has been installed in the tracker mentioned before and a set of measurements was taken in March 2014. The best results, temperature corrected, are shown in FIGURE 8.

The peak efficiency *IV* curve (FIGURE 9) shows a good balance between the short circuit photocurrents of the four cells (if we compare I_{sc} with the current at maximum power point I_{MPP}, the result is I_{sc}/I_{MPP}= 0.95, identical to that of the monomodule) and a good *FF*, better than that of the monomodule (probably owing to a lower temperature operation), but a worse I_{SC}/DNI value (2.98×10^{-3} VS 3.15×10^{-3}). This fact suggests the module could attain efficiencies matching those of the monomodule when the tests are performed under more favorable sky conditions.

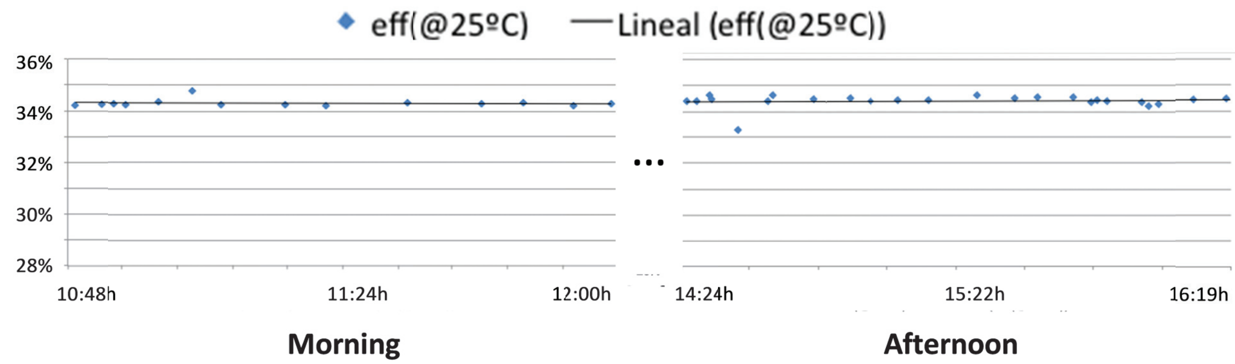

FIGURE 8 Morning and afternoon measurements of the module in a clear March 2014 day. Notice the efficiency values are quite stable and peaks are around 34.8%.

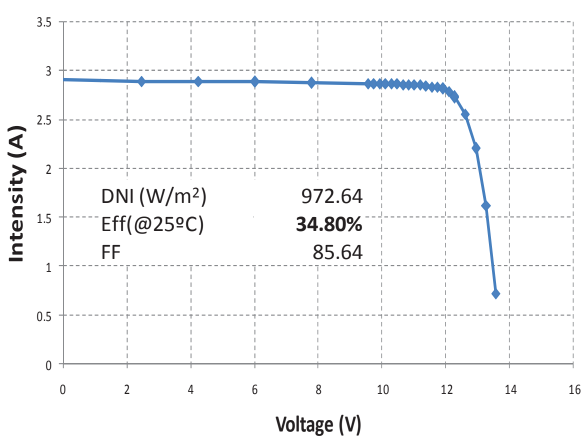

FIGURE 9 IV curve of the maximum efficiency attained in March with the 4-cells module has a *FF* of 85.64%

DISCUSSION

Achieving high efficiency CPV modules and systems relies on the use of high efficiency cells and optics fitting well with the characteristics of sunlight spectral content. Amonix [7] and Semprius [8] hold the current efficiency records at module level (35.9% and 35.5%, respectively). The single-cell module assembled by *LPI* with *Solar Junction* solar cells achieves efficiency values in the range of these records, while the 4-cell module has demonstrated conversion efficiencies quite high but still below those of the current record holders.

TABLE 1. The comparison of performance shows the module efficiency drop is linked to photocurrent generation

	I_{sc}/DNI	I_{MPP}/I_{sc}	*FF*	*Eff*
Monomodule	3.15×10^{-3}	0.95	83.5%	36%
Module	2.98×10^{-3}	0.95	85.64%	34.8%

Looking at the module *FF* and I_{sc}/I_{MPP} figures, the efficiency drop (compared to the monomodule) seems linked to a lower I_{sc}/DNI ratio, which can be in principle blamed to a non-optimal spectral content in the sunlight that was available by the time of the measurement, although the optical efficiency of the 4-lenses panel should be also confirmed and compared to that of the single lens module. More tests are in progress these days to demonstrate the module efficiency can reach the 36% level attained with the single cell module.

ACKNOWLEDGMENTS

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